US Army Corps of Engineers
Engineering and Support Center,
Huntsville

Environmental Security Technology Certification Program

Innovative Navigation Systems to Support Digital Geophysical Mapping ESTCP #200129 Phase II Demonstrations

Revised Report

25 September 2004

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **25 SEP 2004**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Innovative Navigation Systems to Support Digital Geophysical Mapping ESTCP #200129 Phase II Demonstrations**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Simms, Janet * Carin, Larry**	5d. PROJECT NUMBER **MM-0129** 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Corps of Engineers Engineer Research and Development Center ATTN: CEERDC-GS-G 3909 Halls Ferry Road Vicksburg, MS 39180 *Dept. of Electrical Engineering Duke University 176 Hudson Hall, Box 90291 Durham, NC 27708**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **Environmental Security Technology Certification Program 901 N. Stuart Street, Suite 303 Arlington VA 22203**	10. SPONSOR/MONITOR'S ACRONYM(S) **ESTCP** 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**45**	

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ACRONYMS AND ABBREVIATIONS

APG	Aberdeen Proving Ground
BRAC	Base Realignment and Closure Act
CEHNC	Corps of Engineers-Huntsville Center
CWM	chemical warfare materials
DGM	digital geophysical mapping
DGPS	differential global positioning system
DoD	Department of Defense
DSSS	direct sequence spread spectrum
EDM	electronic distance measurement
EM	electromagnetic
EQT	Environmental Quality Technology Program
ERDC	Engineer Research and Development Center
ESTCP	Environmental Security Technology Certification Program
FUDS	formerly used defense sites
FUDS-OE-IT	formerly used defense sites-ordnance and explosive-innovative technology
GFE	government furnished equipment
GIS	Gifford Integrated Sciences
GPR	ground penetrating radar
GPS	global positioning system
IMU	inertial measurement unit
INS	inertial navigation system
ISM	industrial, scientific, and medical
MEMS	micro electro-mechanical system
ms	millisecond
NP	navigation processor
OE	ordnance and explosive
POSLV	Applanix Positioning and Orientation System for Land Vehicle
QA	quality assurance
QAPP	Quality Assurance Project Plan

RF	radio frequency
RFP	request for proposal
RTK	real-time kinematic
RTS	Robotic Total Station
SERDP	Strategic Environmental Research and Development Program
USRADS	UlTrasonic ranging and data system
UXO	unexploded ordnance

ACKNOWLEDGEMENTS

The U.S. Army Corp of Engineers, Engineering and Support Center–Huntsville (CEHNC) managed and evaluated this demonstration effort. ESTCP provided funding through projects 200029, 200129, and 200207 as supported by Dr. Jeff Marqusee and Dr. Anne Andrews, EQT provided funding through AEC by George Robitaille and ERDC by Jay Bennett, and CEHNC provided FUDS OE-IT funding managed by Roger Young. The Center acknowledges the continued contributions and support of these individuals.

Abstract:

This report covers the Phase II demonstrations of innovative navigation systems to support geophysical mapping. Phase II focuses on navigation equipment integrated with geophysical sensors applied in the search for potential ordnance and explosive items. The prior Phase I demonstrations used basic navigation technologies without geophysical equipment.

Eight demonstrators were evaluated for their position performance in the open and in the woods at the McKinley Range, Redstone Arsenal, AL, OE test site for known and unknown surface points and subsurface seeded geophysical anomalies. The technologies included a commercially available RTK GPS with acoustic navigation, a Robotic Total Station laser-based system, a DGPS integrated with an improved low cost Inertial Navigation System, an UlTrasonic navigation with autocorrelation signal recovery, a local area radio frequency positioning system, a laser strobe with enhanced range and four transmitter stations, a low cost GPS/INS integrated with electronic compass and a low cost GPS/acoustic system integrated with an electronic compass.

The demonstrated average error positions of the systems fell into three categories, with normal GPS the least accurate and fitting only for characterization roles. All other systems are capable of area mapping with the UlTrasonic system being limited in work area by its short range. Only the two laser-based line-of-sight systems can support the accuracy and range required for subsurface anomaly interrogation.

Average deviations from the surveyed locations varied from 0.04-1.5 m for known open points, 0.07-3.3 m for unknown open points, and 0.09-5.4 m for unknown obstructed points by the navigation systems. Integrated locations where the positions were picked for surface and subsurface points from the geophysical instrument readings varied from 0.04-3.6 m for known open points, 0.016-4.45 m for unknown open points, 0.37-4.3 m for unknown obstructed points, 0.18-0.95 m for subsurface anomalies in the open and 0.31-1.36 m for the subsurface anomalies in the woods. Subsurface anomalies could not be evaluated for the least accurate system since the large search radius overlapped multiple anomaly locations.

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1.0 INTRODUCTION

1.1 BACKGROUND

General. Unexploded ordnance (UXO) poses a threat to both human life and the environment. Millions of UXO may be located in the United States on active test and training ranges and formerly used defense sites (FUDS). There may be as much as 30 million acres contaminated in more than 1,500 sites. Essentially all project investigations involve the use of digital geophysical mapping (DGM). A major challenge for DGM is the requirement for accurate navigation for sensor position, which is especially problematic with vegetation and under tree canopies. Accurate, inexpensive, and easy-to-use navigation systems with consistent quality are needed for surveys in all terrain and vegetation cover because navigation accuracy is critical to acquiring the accuracy of DGM data required for anomaly discrimination.

The technology will support geophysical mapping of FUDS, active Department of Defense (DoD) installations, defense sites identified under the Base Realignment and Closure Act (BRAC), property adjoining DoD installations, and other federally controlled or federally owned sites that have been impacted by ordnance and explosive (OE) operations.

1.2 OBJECTIVES OF THE DEMONSTRATION

The primary objective of this project is to demonstrate and compare multiple navigation systems to support DGM. Phase I navigation demonstration efforts were fully funded by the ESTCP under project 200129 with participants selected by a full request for proposals (RFP) competitive process. Phase I performed demonstrations with eight vendors/technologies during Fall 2001 with the focus on demonstrating navigation equipment without geophysical equipment integration. Results were presented at the 2002 UXO and Countermine Forum and 2002 Strategic Environmental Research and Development Program (SERDP)/Environmental Security Technology Certification Program (ESTCP) Partners in Environmental Technology Conference.[1]

Phase II also had eight vendor technologies demonstrated from Fall 2002 through Summer 2003. All demonstrators had their positioning systems fully integrated with the typical geophysical sensors used for UXO investigations, EM-61 and the G-858 magnetometer. Demonstration efforts were focused to determine position accuracy for open and wooded areas for known and unknown surface and subsurface items as selected from the captured geophysical data. Phase II efforts were sponsored by the combination of the ESTCP projects 20029, 200129, 200207, the Army Environmental Quality Technology Program (EQT) program, the Corps of Engineers Corps of Engineers-Huntsville Center (CEHNC) funding and in-house support as outlined in the workplan.[2]

[1] Innovative Navigation Systems to Support Digital Geophysical Mapping, UXO/Countermine Forum September 3-6, 2002, Scott Millhouse.
[2] Innovative Navigation Systems to Support Digital Geophysical Mapping, Phase II Demonstrations, Final Workplan, 15 October 2002, Scott Millhouse, (CEHNC).

Phase III demonstrations are being performed from December 2003 through July 2004, as outlined in the workplan.[3] Efforts include navigation equipment from four vendors fully integrated with a government-furnished Geometrics 858 cesium vapor magnetometer. Demonstrations are performed in a consistent manner to minimize the effects of the geophysical sensor.

There are three levels of accuracy needed to support the OE program as outlined in the original RFP:

1. The screening level determines areas of interest through application of either airborne sensors or ground-based sensors surveying corridors, transects, or meandering pathways. For this demonstration, this level is demonstrated by the low-cost and low-accuracy characterization system by Paper Pilot Research, Inc.

2. Area mapping is performed by man portable and towed array systems. The remaining demonstrators support the typical field area mapping need. Some have clear advantages for high production open areas and some for smaller areas where reduced productivity is acceptable, e.g., in the woods.

3. Highly accurate, dense data is acquired to interrogate and then, by postprocessing, discriminate a previously located target anomaly. Only the laser systems demonstrated in Phase II by ArcSecond and Shaw/IT can acquire position data to the required accuracy level. Productivity and range is reduced with data acquired over a small area that was selected from previous mapping efforts.

Position tolerance of 0.5m, 0.05 m and 0.02 m is desired for these scenarios, respectively, as outlined in the original RFP. For this demonstration, tolerance is defined as deviation from the civil surveyed position of the known and unknown points. Accuracy (or average error) is the demonstrated deviation from the location of the surveyed points.

Phase I demonstrations at the McKinley Range Test Site in Huntsville, Alabama, with only navigation equipment, have shown that these goals are still somewhat ambitious but they can be approached. For the three mission scenarios, the best system average error was 1m, 0.04 m, and 0.006 m demonstrated in the open areas with the known points and 3 m, 0.6 m, and 0.09 m demonstrated in the wooded areas for unknown points. The demonstrations results supported additional development of navigation equipment with emphasis on obstructed and wooded areas.

For Phase II at McKinley Range, demonstrators were challenged to integrate with the EM-61 and G-858 geophysical sensors and survey to locate 10 known and 15 unknown surface points and 20 known and 130 unknown subsurface anomalies. Subsurface anomaly location evaluations were not possible for the Paper Pilot characterization system because of the inaccuracy of the basic global positioning system (GPS) equipment. The error radius was too large for this system to allocate the locations to the individual anomalies. The characterization mapping system demonstrated an average error of 1.5 m for the known surface points and 3.3 m for unknown

[3] Innovative Navigation Systems to Support Digital Geophysical Mapping, Phase III Demonstrations, Final Workplan, 4 November 2003, Scott Millhouse, CEHNC.

surface points in the open, with 5.4 m in the woods by navigation alone. Accuracies of 3.6 m for the known open and 4.5 m for the unknown open locations were demonstrated from picked locations in the integrated geophysical sensor readings. The area mapping systems demonstrated an average error of 0.04 m–0.3 m for the known surface points and 0.09 m–0.79 m for unknown surface points in the open with 0.1 m–1 m in the woods by navigation alone. For locations picked from the integrated geophysical sensor readings, accuracies were 0.37 m–1.39 m. Average error for subsurface anomalies were 0.18 m–0.42 m for known open and 0.32 m–0.95 m for unknown open, with 0.31 m–1.36 m for unknown wooded locations.

The following goals are desired for high-performing equipment, as stated in the Navigation RFP:

- 10-minute setup
- 1000'+ range per setup
- Ability to map a 5-acre area
- Ability to have multiple crews working in the same area without interference
- Cost of less than $20,000 per system
- Voice communication capability without interference
- Go-to-point capability (reacquisition)
- Real-time data transmission to a central location (to allow real-time geophysical analysis)
- Ability to capture the z or elevation data along with position
- Ability to determine relative position of individual sensor heads when coupled with geophysical instrumentation (skew, lifting tilting, etc.)
- Flexible use with geophysical instruments such as mag, electromagnetic (EM), ground-penetrating radar (GPR) etc.)
- Selectable accuracy mode to allow higher accuracy for interrogation of anomalies (most likely at a slower rate of sensor travel speed)
- Real-time track map display for surveyor
- Ability to support real-time grid generation and display of geophysical data when coupled with geophysical sensors
- Capability of the system to inform users when accuracy levels are being achieved (to avoid the collection of bad data)
- Capability to survey in wooded conditions with varying degrees of topography

Systems being demonstrated and evaluated include the following:

- CEHNC: Independent Baseline, commercially available NovAtel real-time kinematic (RTK) GPS and acoustic navigation
- Shaw/IT Group ESTCP Project 200129: Robotic Total Station laser-based system
- Blackhawk ESTCP Project 200129: DGPS integrated with an improved lower cost inertial navigation system (INS)
- Where Company ESTCP Project 200207: Improved UlTra ultrasonic navigation
- ENSCO, Inc. ESTCP Project 200029: Local area radio frequency (RF) positioning system
- ArcSecond (DERP [FUDS-OE-IT funded]): Constellation (laser GPS) with enhanced range and four transmitter stations

- Paper Pilot ([ERDC]-EQT funded): Low-cost GPS/INS integrated with electronic compass (for characterization use)
- Gifford Integrated Sciences (GIS) (ERDC-EQT funded): GeoVizor—Low-cost GPS/acoustic integrated with electronic compass (for characterization use)

1.3 REGULATORY DRIVERS

The objective of this project is more efficient and more accurate OE field operations, better technical remediation performance, and reduced cost. Precise navigation and positioning technology is an important part of the infrastructure of OE remediation efforts as an enabling tool to allow faster, better, and cheaper detection, characterization, and excavation. Regulatory issues do not affect the need for this technology.

1.4 STAKEHOLDER/END-USER ISSUES

Results of this demonstration will provide end users an understanding of the technical, logistical, and financial impact of these technologies to allow informed decisionmaking by end users for appropriate applications.

2.0TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

This work is for demonstration of existing systems with minor modifications, new technique development, and software enhancement. The demonstrated systems cover known technologies for positioning. Six basic navigation technologies are being demonstrated: GPS, Laser, UlTrasonic, Inertial, Compass, and Radio. The demonstrators apply them as follows: four systems are DGPS, GPS, and GPS hybrids; two are line-of-sight laser-based, with one using traditional single unit surveying technology and the other multiple laser transmitters to create a form of laser GPS; three systems use UlTrasonic positioning as either a primary or secondary navigation system; two systems use inertial navigation systems to supplement the base GPS navigation system with positioning when satellites are obstructed; two systems use electronic compasses for a direction vector; and one system uses radio frequency for positioning. The following is a brief summary of each demonstrator's system.

2.1.1 CEHNC

Commercially available RTK GPS and acoustic navigation were demonstrated to provide an independent performance baseline. These two technologies are the systems that historically have a wide application in OE geophysical mapping. They are not integrated as one system. Essentially, RTK GPS is used for all areas with a clear view of the satellite constellation. The acoustic system is used to cover all obstructed (wooded) areas. Huntsville's application for this demonstration was performed by independent government personnel with government equipment. We explored the limitations of DGPS in obstructed areas by continuing to map within the trees. Those areas were then resurveyed using the acoustic system with stationary receiver locations surveyed by civil methodology. The following is a general description of both systems.

2.1.1.1 RTK DGP Description

The GPS system is a spread-spectrum distance measuring system, which measures the distance from a user to several satellites. Knowing the positions of the satellites, the position of the user is computed. GPS measures the distance from the satellites to the user using one-way communications (from the satellite to the user), generating the so-called pseudo-range, and the unknown clock time of the user is solved for in the solution. The RTK portion of the GPS is accomplished by a base station GPS unit occupying an existing known bench mark, recording and relaying its measured position, and creating a differential correction from the known position. It then sends that correction to the rover unit, which applies the correction to its calculated position to derive a more precise DGPS position. The fluctuations caused by changes in the satellite constellation can then be processed from the rover's recorded position to eliminate errors and provide a more accurate position. DGPS-RTK and postprocessed GPS can perform, as advertised by the vendors, to centimeter grade positioning for stationary locations. We used a government-owned NovAtel 20-cm system for this demonstration. The expected accuracy for areas with an unobstructed view to the satellite constellation is 0.2 m.

2.1.1.2 UlTrasonic Ranging and Data System (USRADS) Description

This navigation system (shown in Figure 2-1) utilizes UlTrasonic techniques to determine the location of a geophysical instrument each second. It consists of three basic elements–a data pack, up to 15 stationary receivers, and a master control center. The data pack is mounted on the EM-61 back pack with the transducer mounted approximately 1 m above the EM-61 coil. The data pack fires the transducer and by monitoring the time-of-flight, the location of the geophysical sensor can be determined. The stationary receivers are placed throughout the survey area with about 10 required per acre. A minimum of two is required to be on known points. The system software automatically determines the locations of the stationary receivers by utilizing the time-of-flight information between all stationary receivers. Finally the master control center and laptop computer acts as the master timer between the components, as the data processor and as the data collector. The computer computes the sensor position location and displays the survey data. Position accuracy of 0.15 m is expected with proper stationary receivers distributed at up to a 150' spacing.

Figure 2-1. Government USRADS in Woods.

2.1.2 Shaw E&I-ESTCP Project 200129

The Robotic Total Station (RTS) laser-based system was demonstrated in Phase I and selected for further development. This Phase II demonstration tests the developed enhancements.[4] Shaw E&I (formerly IT Corp.) demonstrated the Leica TSP1100 dual-laser RTS with a very high accuracy and long range. It is a pure line-of-sight application but, even with obstructions caused by tree trunks and branches, it provided the highest accuracy in the wooded areas with a reasonable range. This was attributed mostly to software enhancements that allowed the base unit to maintain track of the rover by predicting its location when emerging from obstructions. The RTS was successfully demonstrated in Phase I with a magnetometer (G858) sensor. For Phase II, an electromagnetic (EM61) sensor was demonstrated. Since Phase I, they have developed capability to integrate both sensor systems with the navigation gear. They also have developed standard operating procedures for using the technology with these sensors. They

[4] Innovative Navigation Systems, Draft Phase 2, Final Report, April 2003, John E. Foley, Ph.D., Shaw Environmental and Infrastructure Corp.

demonstrated the capability to execute geophysical surveys in open areas as well as in lightly wooded conditions.

An RTS operates under a different concept from either GPS or the UlTrasonic systems. It essentially is a survey station that derives its position from traditional survey methodology and then tracks the relative position of the sensor. The robotic portion maintains track on the moving prism. The unique qualities of this demonstration are the procedural and software modifications that allow the RTS to maintain lock in heavy vegetation by predicting the location of the sensor and then reacquiring it. Figure 2-2 shows the basic concept.

Figure 2-2. Shaw Robotic Total Station.

2.1.3 Blackhawk ESTCP Project 200129

This technology, which was demonstrated in Phase I, was selected and funded for further development and testing in Phase II.[5] The improved system demonstrated DGPS integrated with an improved lower cost INS. These tests augmented the testing performed in Phase I with the integration of the EM61 geophysical sensor with an INS augmentation at less than half the cost of the Phase I demonstration GPS/INS positioning system.

In Phase II, a man-portable modified version called the POSLV 310 UXO of the Applanix Positioning and Orientation System for Land Vehicle (POSLV) was developed (Figure 2-3). The man-portable INS utilizes (where available) GPS data to improve position accuracy. An INS contains two core components, an inertial measurement unit (IMU) and a navigation processor (NP). The IMU contains three accelerometers and three gyros, whose respective input axes form an orthogonal triad, plus digitization and digital interface electronics. The accelerometers measure the specific force that the IMU experiences, comprising accelerations and gravity with respect to an inertial reference. The gyros measure the angular rate that the IMU experiences, comprising its angular rate with respect to the earth plus the earth's angular rate with respect to the inertial reference. The NP receives the inertial data and performs two functions. First it performs an alignment, during which it establishes an initial position and orientation using the local gravity vector as the vertical reference and North component of the earth rate vector as the

[5] Demonstration and Development of Innovative Navigation Equipment and Methodologies to Support Accurate Sensor Tracking in Digital Geophysical Mapping (DGM) Surveys, Phase 2, Engineering Evaluation Report Final Draft, Jan 14, 2003, Mark Blohm, Blackhawk Geosciences.

heading reference. Having established a navigation frame of reference that is locally level and having a known heading with respect to North, the NP then transitions to its free-inertial navigation mode. It solves Newton's equations of motion in the navigation frame on the earth from the measured specific force and angular rate data to generate a current position, velocity, and orientation solution at a specified sampling rate.

Figure 2-3. Blackhawk/Applanix GPS/INS System.

2.1.4 Where Company ESTCP Project 200207

This separate ESTCP project has common navigation goals. The Long Range UlTra System (Figure 2-4) is an improvement on the UlTra System developed by Where Company for Phase II.[6] The system consists of a reference station mounted on a tripod and a small Rover unit mounted over the geophysical sensor (the EM-61 for this demonstration).

The reference station has five orthogonal arms with UlTrasonic receiver pods at the end of each arm. Each receiver pod contains six UlTrasonic receivers mounted circumferentially. There are four UlTrasonic transmitters mounted near the center of the array and pointing along each of the horizontal arms. The reference station also contains a low-power FM radio for timing and data transfer operations. The Rover unit, mounted directly over the geophysical sensor contains six UlTrasonic transmitters mounted circumferentially and a low-power FM radio.

An inaudible beep is emitted by the Rover once each second, along with a start signal on the radio, under instruction by the computer. When the reference station hears the radio start signal, it starts clocks for each of the five receiver pods. The reference station then measures the time it takes the ultrasonic beep to get to the five receivers mounted on its orthogonal arms. A second ultrasonic pulse emitted by the reference station is used to calculate the current speed of sound by measuring the time taken for the pulses to travel the known arm lengths. The timing values are then transmitted back to the Rover and on to the computer where the Tracker program calculates the coordinates displaying the location.

[6] Long Range UlTra System, Final Report, Revised 29 April 2004, Scott Millhouse, CEHNC.

Figure 2-4. Where Company UlTra Ultrasonic System.

2.1.5 ENSCO ESTCP Project 200029

This separate ESTCP project with common navigation goals utilized a local-area radio frequency precise positioning and communication system called Ranger demonstrated with an EM-61 for Phase II.[7] It exploits a unique direct sequence spread spectrum measuring system to provide precision geolocation and simultaneous data communications. Multiple base-station radios are used to measure their distance to one or more mobile radios. These multiple distance measurements can then be used to compute the coordinates of the mobile radios. Repeated sequential distance measurements and coordinate computation enables tracking the mobile radio's path. This navigation system is directly integrated with a data logger and geophysical instrumentation for the Phase II demonstration. Figure 2-5 shows the system.

Figure 2-5. ENSCO Ranger System.

The Ranger communications architecture is based on direct sequence spread spectrum (DSSS) in the 2.4 GHz industrial, scientific, and medical (ISM) band. This allows Ranger to operate as an unlicensed transmitter under FCC rules with a 1-watt transmit power. Core circuitry takes advantage of widely available and inexpensive components commonly used in 802.11b wireless network products.

[7] UXO Precise Position Tracking Demonstration, Draft Final Report, 1 Apr. 2003, ENSCO Inc., David W.A. Taylor, PhD, PG.

The key element of Ranger is the ability to accurately measure distance. Methods for using a DSSS radio for semi-precise time-of-flight measurements are well understood for coarse measurement. Ranger differs in that a fine measurement is made to estimate more precisely the time-of-arrival (and hence the distance traveled) of a signal. It is this fine measurement that provides the submeter accuracy of Ranger.

2.1.6 ArcSecond

The original Vulcan Laser Station was demonstrated in Phase I with dual transmitters and then with enhanced range and four transmitter stations as the Constellation System for Phase II (see Figure 2-6).[8] Phase I was funded by ESTCP project 200129 with Phase II 100% funded by CEHNC FUDS-OE-IT. This highly accurate system is being developed for demonstration to cover large areas with additional transmitter capability and higher power output. Range has been greatly increased by these enhancements. Accuracy is high enough that it currently meets the goals for gathering data for geophysical anomaly discrimination for small open areas.

Figure 2-6. ArcSecond Constellation System.

Constellation works very much like a portable, highly accurate RTK-GPS alternative. The portable nature of the system allows the user to map areas where traditional methods (optical, acoustical, and GPS-based) dramatically degrade or fail—primarily under and near tree canopy, but also in relatively open areas with poor satellite visibility. The system's ability to support any number of 3D sensors simultaneously opens two intriguing benefits for UXO: (1) the ability for multiple users to map simultaneously, and (2) the ability to track the full position and orientation of a geophysical sensor (e.g., to allow 3D discrimination of UXO).

The system consists of stationary laser transmitters/beacons (like GPS satellites) and portable sensors that can be carried or mounted on objects. The system can support any number of sensors working off the same transmitters, so multiple users could be conducting geophysical mapping surveys in the same work area. For a sensor to calculate its 3D position, it must see at least two laser transmitters. Consequently, for open areas, two transmitters work well; under tree canopy or in areas where line-of-sight is restricted (e.g., close to buildings), three or four

[8] McKinley Range Navigation Demonstration, 14 Nov. 2002, Edmund Pendelton, ArcSecond Inc.

transmitters provide fuller coverage. Position location is by triangulation from the fixed transmitters.

2.1.7 Paper Pilot

Under Phase I, funded by ESTCP, a low-cost, portable GPS and INS was developed. The prototype was constructed by combining a low-cost INS and a GPS receiver. Three reasons for combining an INS and a GPS receiver are: (1) the combined system can achieve greater accuracy than the GPS or INS alone; (2) platform attitude can be determined by the INS and (3) the INS can provide a position estimate when GPS service is interrupted. Efforts were focused for providing a position estimate. For Phase II, as funded by EQT, improvements were made to the system, such as integration of an electronic compass and integration of the equipment with an EM-61 DGM sensor for field testing and demonstration.[9]

The inertial measurement unit is the IMU400CA-100 model from Crossbow Technology, Inc. The IMU400CA contains six sensors, three micro electro-mechanical system (MEMS) accelerometers and three solid-state angular rate gyros. MEMS terminology refers to very small mechanical devices, in this case vibrating beams, constructed in silicon and mounted on a computer chip. The IMU400CA sensors measure longitudinal, lateral, and vertical accelerations as well as pitch, roll, and yaw angular rates. The Garmin GPS 25-HVS receiver tracks up to 12 satellites and provides position updates every second. The Honeywell MMR 3300 electronic compass provides heading. The mobile computer is a Compaq iPaq 3765 handheld.

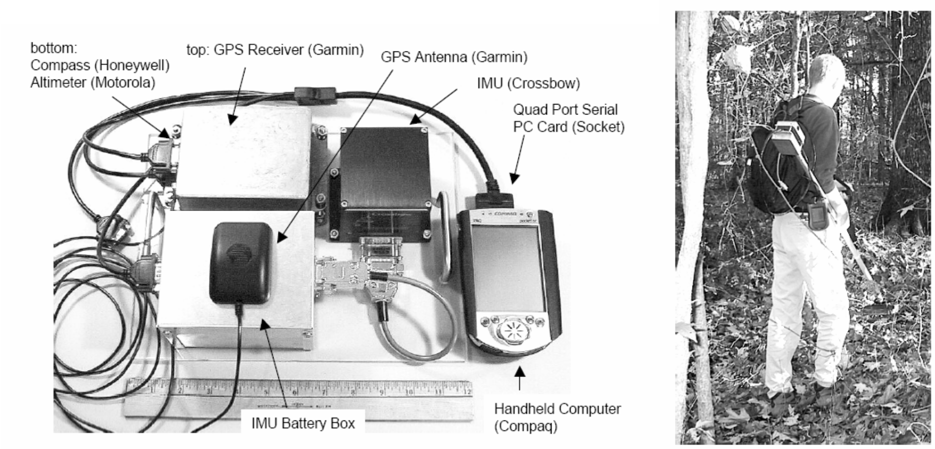

Figure 2-7. Paper Pilot System.

The demonstrator has assembled the system using the same low-cost GPS engine as in the handheld device but as available in PC cards. This is a low-cost proof-of-concept demonstration of the INS integration and postprocessing software analysis. This approach of assembling the GPS, INS, and computer/data recorder into a backpack system would permit easy integration with any geophysical instrument to create a low-accuracy, low-cost system (approximately

9 Innovative Navigation Systems to Support Digital Geophysical Mapping, Navigation System Report, 15 Nov. 2002, Mark R. Andersen, Paper Pilot Research Inc.

$5,000). The INS, the principal component cost, maintains the base unit's accuracy when satellite lock is lost.

2.1.8 Gifford Integrated Sciences GeoVizor

This system, shown in Figure 2-8, is a low-cost DGPS/acoustic hybrid system integrated with an electronic compass. Its development and demonstration has been fully funded by EQT. The primary system, DGPS, locates the operator within the global coordinate system. The secondary system locates the instrument head relative to the DGPS antenna or a fixed stationary point. The primary positioning system was CEHNC's government-furnished equipment (GFE) 20 cm-capable NovAtel DGPS system. Secondary relative positioning is provided by the Hexamite ultrasonics. The ultrasonic positioning system is designed to provide accurate position information up to a 16 m range. In the hybrid system this component is used to track the X, Y, and Z positions of the instrument head. It is also used to accurately determine the pitch and roll of the head or antenna surface. The real-time display allows the operator to "see" the survey as it is taking place through a head-mounted computer display. The operator has various views of the data for selecting different survey objectives. The extremely rapid refresh rate of the Ultrasonic systems allows the operator to move the geophysical instrument in real time while keeping track of its position. The combination of the Ultrasonic position information with the geophysical signal results in a volumetric representation of geophysical response around a target.

The primary positioning system is the CEHNC NovAtel RTK DGPS system as described in Section 2.1.1.1, with the secondary positioning system utilizing the following hardware:

- Hexamite HE860 series positioning device (three required, one for each axis)
- Hexamite HE240SRX receiver (three required, one for each HE860)
- Hexamite HE240STX transmitter, for use in tethered mode
- Hexamite Miniature Ultrasonic Transponder Positioning Tag, for use in untethered mode (variable number required, depending on specific setup)
- MapStar compass module (±/- .3 degrees accuracy)

The complete GeoVizor system, as demonstrated for Phase II,[10] is a backpack or pulled cart system with the following components:

- Laptop computer
- Heads-up display
- Ultrasonic positioning systems (2)
- Electronic compass
- DGPS system (NovAtel)
- Integration and visualization software
- Geophysical instrument (Geometrics 858)

[10] GeoVizor McKinley Range Prove-out, July 13, 2003, Matthew Gifford, Gifford Integrated Sciences.

Figure 2-8. GIS GeoVizor System.

2.2 PREVIOUS TESTING OF THE TECHNOLOGY

A low-cost demonstration of eight vendors' navigation technology was demonstrated at the McKinley Range during October and November 2001 as Phase I, funded by ESTCP.

Table 2-1 lists the demonstration vendors, their system type, and technology.

Table 2-1
Phase I Demonstrators

Vendor	System Name	Technology
CEHNC	Garmin GPS III	Handheld GPS
ARINC, Inc.	LEOPARD Lite	GPS with satellite communications
Paper Pilot Research Inc.	New Integration	GPS and inertia guidance
ENSCO, Inc.	Tracker	Radio frequency
IT Group	Leica RTS	Robotic total station
ArcSecond, Inc.	Vulcan/LaserStation	Line of sight laser
Parsons	Trimble INS/GPS	DGPS and inertia guidance
Blackhawk	Applanix INS/GPS	DGPS and inertia guidance

The vendors demonstrated just navigation equipment. Table 2-2 shows the demonstrated average error for the unobstructed known points from Phase I.

Table 2-2
Unobstructed Range and Average Error

Vendor	System Name	Range	Average Error
CEHNC	Garmin GPS III	Unlimited	0.7 m
ARINC, Inc.	LEOPARD Lite	Unlimited	11.7 m

Paper Pilot Research Inc.	New Integration	Unlimited	1.0 m
ENSCO, Inc.	Tracker	450 m demonstrated	0.25 m
IT Group	Leica RTS	450 m demonstrated	0.004 m
ArcSecond, Inc.	Vulcan/LaserStation	45 m demonstrated	0.006 m
Parsons	Trimble INS/GPS	450 m demonstrated	0.04m
Blackhawk	Applanix INS/GPS	450 m demonstrated	0.22 m

Range is limited only by satellite view for the first three systems utilizing standard GPS. The last two with INS/GPS are limited by the DGPS base station radio link. ArcSecond was severely limited by the range of their base units. The 450 m demonstrated by the remaining systems was the maximum distance that could be demonstrated at the site and does not represent the maximum range of the systems.

Table 2-3 shows the demonstrated average error for the obstructed unknown points.

Table 2-3
Obstructed Range and Average Error

Vendor	System Name	Range	Average Error
CEHNC	Garmin GPS III	100 m	2.1 m
ARINC, Inc.	LEOPARD Lite	100 m	25.9 m
Paper Pilot Research Inc.	New Integration	100 m	3.3 m
ENSCO, Inc.	Tracker	50 m	0.9 m
IT Group	Leica RTS	100 m	0.09 m
ArcSecond, Inc.	Vulcan/LaserStation	45 m	0.08 m
Parsons	Trimble INS/GPS	100 m	0.64 m
Blackhawk	Applanix INS/GPS	100 m	0.67 m

2.3 FACTORS AFFECTING COST AND PERFORMANCE

Application costs and productivity were recorded for the Phase II demonstrations. These include daily/weekly/monthly technology costs for rental, purchase and maintenance; technology availability and downtime considerations; survey productivity factors, including setup, survey area limitations, operating personnel labor requirements, cost; and data processing considerations for position and geophysical instrument integration. Details are shown in the vendors' reports.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Determination of the advantages and limitations of the demonstration technologies is a goal of this project. The following is an overview comparison of the RTK DGPS and Ultrasonic baseline systems CEHNC demonstrated as the benchmark for comparing advantages and limitations. Both are readily available and widely used for similar field applications.

Table 2-4
Comparison of DGPS and Ultrasonic

	RTK DGPS	Ultrasonic
Range of operation	Limited to radio link, 2-7 miles	30-40 m
Precision	2-20 cm	10-20 cm
Number of transponders in addition to mobile	1 (base station)	12
Effect of vegetation/canopy	Blocked	Some loss of range
Purchase cost	$35,000	$70,000

3.0DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

Technical performance was measured relative to performance objectives identified in the Phase I RFP. Table 3-1 outlines the objectives.

Table 3-1
Performance Objectives

Type of Performance Objective	Performance Criteria	Expected Performance
Quantitative	Unobstructed range of operation	100-1000 m
	Unobstructed average error	0.5-200 cm
	Obstructed range of operation	50-500 m
	Obstructed average error	1-200 cm
	2D position error	1-200 cm
	Setup time	10-30 min
	Multiple crew capability	Yes or No
	Voice communication	Yes or No
	Ability to capture elevation data (3D)	Yes or No
	Selectable accuracy	Yes or No
	Flexible use of geophysical equipment	Yes or No
	Real-time display of geophysical grid data	Yes or No
	Ability to display position data in near-real-time on mobile data logger	Yes or No
	Ability to display position data in near-real-time on remote computer	Yes or No
	Ability to survey grids in wooded areas	Yes or No
	Integrated with G858	Yes or No
	Integrated with EM61	Yes or No
Semiquantitative	System easy to set up and calibrate by two-person team	Yes or No
	System easy to operate by two-person crew	Yes or No
Qualitative	Reoccupation of position easily accomplished	Yes or No

The project objectives are outlined in Paragraph 1.2 as presented in the Navigation RFP. The demonstrated position locations were compared to the known locations of all target surface features and subsurface anomalies. Deviations from the true locations were identified and categorized separately for surface features in the open and wooded areas, for the dig list locations of the subsurface anomalies in the open and wooded areas, and for the reacquired locations of the anomalies in the wooded area. The coordinate and radial deviations were calculated for each point, and the resulting average location error and standard deviation were calculated for each location category for each demonstrator.

3.2 SELECTING TEST SITES

Criteria for selecting a test site are the following:

- Accessible to all project participants
- Sufficient space to accommodate the distances required for the planned tests
- Combination of open areas and areas with a variety of vegetation densities
- Buried metallic targets that can be used to compare sensor data with and without the presence of navigation equipment
- Moderate terrain so elevation effects will not dominate the demonstration
- A controlled site with locations of items unknown to the demonstrators so the site can be revisited to gauge improvement and to compare to other technologies

Our selected test site—the McKinley Range, Redstone Arsenal, Huntsville, Alabama—meets all these selection criteria.

3.3 TEST SITE HISTORY/CHARACTERISTICS

CEHNC has established a series of test plots on a portion of the McKinley Range. The site is broken into five test areas with various objectives. The individual grids are defined by civil surveyed steel pin corner points outlining four 100 ft by 100 ft grids. The fifth area is a figure eight traverse into the woods. An adjacent unseeded open area to the west provides a traverse extension for range evaluations along with an eastern traverse extension along the access road. The individual points for the grid corners and traverse were used. Demonstrators were only provided with the locations of the corners of the 100 ft by 100 ft grids. All figure eight traverse points were challenging because of a restricted view of the horizon and line-of-sight by cultural or natural features.

The following areas make up the McKinley Range geophysical test area: Grid 1 is seeded with inert OE items from 20 mm to 2,000 lb bombs from a few inches to nearly 10 ft deep. The grid is broken into two lanes, known and unknown and has been used for instrument validation since 1994. Grid 2 is seeded with items typical for chemical warfare materials (CWM) sites including chemical test kits, pigs, and containers. Grid 3 is a series of sand trenches of various gradations that are also seeded with CWM stimulants. Grid 4 is seeded with traditional OE items but is constructed to be more representative of an impact area and has numerous areas of ferrous surface clutter. Area 5 is a figure eight meandering path traverse that travels through open area into light and heavy canopy for use in determining navigation accuracy and reacquisition of anomalies. Area 5 was seeded with approximately 60 “blind” subsurface point source anomalies for the Phase II demonstrations. They consisted of either 18" long #4 rebar or 1" pipe driven to below the ground surface. All grids have been surveyed many times with multiple instruments, including the EM-61 and magnetometers. Grids 1, 4, and 5 were used in Phase II for surface point and subsurface anomaly position locations. These grids include 10 known and 15 unknown surface points and 20 known and 130 unknown subsurface anomalies.

The corner points for the first four areas are perfect for determining navigation accuracy and the effects on the geophysical equipment because they are flat and open, making it possible to

determine the effects of the system components benchmarked against the known seeded item locations and the numerous geophysical equipment data sets for comparison. Area 5 allows us to assess the impact caused by vegetation and cultural obstructions.

Figures 3-1, Figure 3-2, Figure 3-3, and Figure 3-4 show the geophysical test grid and layout, an overview of the entire site, a typical traverse of area 5 or the figure eight as performed in a prior demonstration, and photos showing the open and wooded areas.

Figure 3-1. Area 1-4—Typical Photographs.

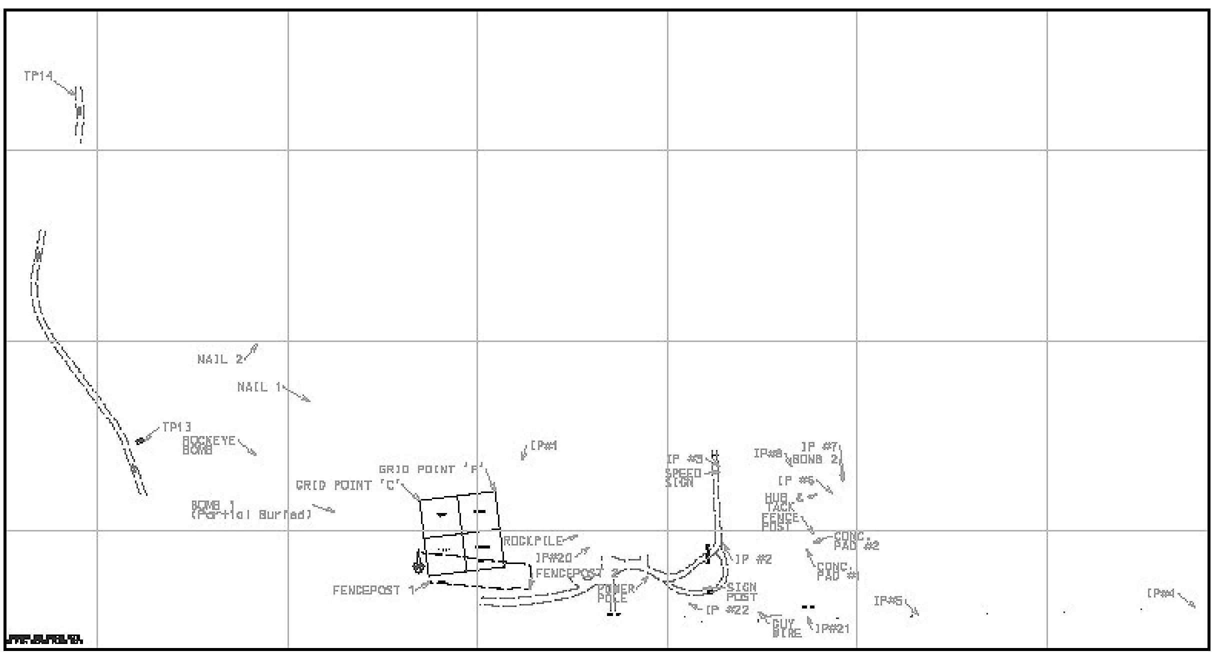

Figure 3-2. McKinley Range Test Site Overview.

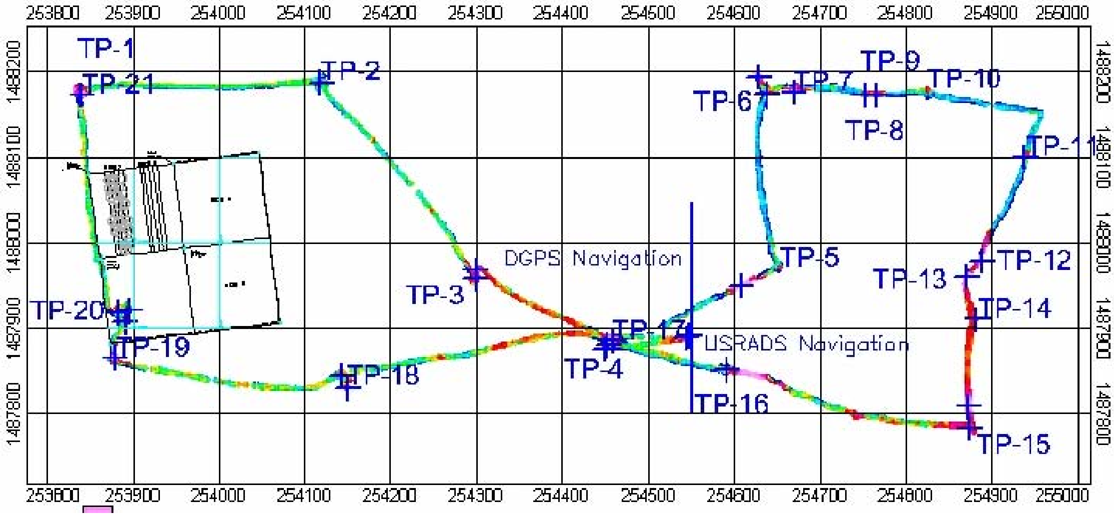

Figure 3-3. Four Grids and Navigation Traverse.

The west side is open allowing for DGPS satellite view while the east side is in the woods. The break-line shows transition from DGPS to USRADS navigation into the woods from a previous test. All points are accurately surveyed in by traditional civil surveys to 0.01' accuracy using a Total Station electronic distance measurement (EDM).

Figure 3-4. Photographs of Wooded Areas.

3.4 PRESENT OPERATIONS

The McKinley Range OE test grids are maintained to provide quantitative, benchmarked evaluation of sensors and DGM systems and components. Numerous prior demonstrations have been conducted at this facility under the supervision of CEHNC.

3.5 PREDEMONSTRATION TESTING AND ANALYSIS

Previous testing has been performed at this location under Phase I as described in Section 2.2.

3.6 TESTING AND EVALUATION PLAN

3.6.1 Demonstration Setup and Start-Up

Demonstration setup requires installation of the fixed position sensors, as appropriate, and calibration of the systems. All equipment is battery powered and requires no external power.

3.6.2 Period of Operation

Table 3-2 shows the demonstrations periods of operation.

Table 3-2
Demonstration Dates

Demonstrator	System Name	Demonstration Dates
CEHNC	DGPS	October 3-4, 2002
CEHNC	USRADS	April 28, 2003
Shaw/IT	RTS	October 16-18, 2002
Blackhawk	DGPS/INS	October 29-31, 2002
Where Company	UlTra	April 30-May 2, 2003
ENSCO	Tracker	January 28-31, 2003
ArcSecond, Inc.	Constellation	October 21-23, 2002
Paper Pilot Research Inc.	GPS/INS/Compass	November 7-8, 2002
GIS	DGPS/Acoustic/Compass	June 24-30, 2003

3.6.3 Amount/Treatment Rate of Material to be Treated

Not applicable

3.6.4 Residuals Handling

Not applicable

3.6.5 Operating Parameters for the Technology

This varies among the demonstrated systems.

3.6.6 Experimental Design

Tests were performed to validate performance as outlined in Table 3.1. The government previously surveyed all points by traditional civil surveying techniques using a Total Station EDM. Tests were adapted to meet individual system needs. The following outlines basic tests.

Test 1: Distance and average error with standalone positioning system

Testing occurred in a flat, open area chosen so the limiting constraint on the measurement result will be the navigation technology. Range of operation was determined by maximum distance at which the system successfully made a distance measurement. Accuracy of measurements was determined by comparison to the known point locations.

Test 2: Navigation equipment integrated with geophysical equipment

Test 1 was repeated with the geophysical equipment integrated. In addition, grids 1 and 4 were completely geophysically mapped by the systems. The field data was analyzed with the geophysical anomalies selected and annotated to dig sheets with predicted coordinate locations.

Test 3: Ability to reoccupy location and reacquire geophysical anomalies

A sample of the points previously collected was reacquired with the navigation system in a standalone mode and with the integrated system. This test demonstrated the ability to navigate to specific predetermined targets.

Test 4: Impact of vegetation and obstructions

Test 4 repeated the activities of Tests 1, 2, and 3 to evaluate the impact of vegetation on measured data. Results of accuracy, range of operation, and other performance objectives were compared from these vegetated areas to the clear areas.

3.6.7 Sampling Plan (not for UXO identification/discrimination)

This section is not applicable.

3.6.8 Demobilization

Demobilization requires repacking equipment in shipping cases and departing the site. There should be no lasting impact to the site from this demonstration.

3.7 SELECTION OF ANALYTICAL/TESTING METHODS

This section is not applicable.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE CRITERIA

The performance objectives in Table 3-1 define the criteria by which performance were be evaluated.

4.2 PERFORMANCE CONFIRMATION METHODS

Performance was evaluated by comparison of the observed measurement parameters for each test in Section 3.6.6 with the reference measurements and the actual positions of surface and subsurface items.

4.3 DATA ANALYSIS, INTERPRETATION, AND EVALUATION

Direct comparison was used to analyze data. In cases where multiple measurements were made, statistical mean and standard deviation were computed.

4.4 PERFORMANCE ASSESSMENT

This performance assessment has been independently compiled by CEHNC from field observations, the demonstrator's reports, and independent analysis of the provided data with comparison to the known and unknown survey points and subsurface seeded item locations.

The CEHNC and GIS DGPS demonstration used the government's NovAtel 20-cm system. The average error approximated the Trimble 2-cm capable system used by Blackhawk for positions when both captured locations dynamically. The Paper Pilot system used the much less accurate GPS for base positioning. Shaw's RTS was the most accurate in the open since it is an application of a survey instrument. Where Company's UlTra is limited to small local area applications due to its short range and moderate accuracy. The ENSCO Tracker approximated the dynamic average error of the Trimble 2-cm DGPS. ArcSecond more than doubled the range demonstrated in Phase I, while maintaining the accuracy of survey instruments with the flexibility of a large mapping area. All systems met area mapping needs except Paper Pilot for accuracy and Where Company for range.

The government placed and surveyed in the locations of 25 surface and approximately 150 subsurface emplaced items. Out of these 175 points, the contractors were provided with 10 known surface points (rebar pins) for equipment reference, as well as the item types and locations of the subsurface emplaced items in Lane 1 Grid 1 (20 mm to 2,000 lb), as outlined in Paragraph 3.3. The government retained the locations of 15 unknown surface points (pins, nails and pipes) and 130 unknown subsurface anomaly locations for independent performance evaluations. Deviations from the surveyed locations of these points were calculated and averaged and reported with the standard deviations of the values. Approximately 70 subsurface items in Grids 1-4 were OE or simulants. Area 5 is seeded with approximately 60 "blind" subsurface point source anomalies. They consisted of either 18" long #4 rebar or 1" pipe driven to below the ground surface.

4.5 PERFORMANCE CRITERIA—UNOBSTRUCTED RANGE OF OPERATION

DGPS and GPS are not limited by distance but by satellite visibility and, in the case of DGPS, by the radio link transmission range to the base station. Table 4-1 shows the performance criteria for an unobstructed range of operation.

Table 4-1
Unobstructed Range of Operations

Demonstrator	System Name	Range
CEHNC	DGPS, USRADS	Unlimited, 45 m
Shaw/IT	RTS	450 m
Blackhawk	DGPS/INS	Unlimited
Where Company	UlTra	36 m
ENSCO	Tracker	450 m
ArcSecond, Inc.	Constellation	120 m
Paper Pilot Research Inc.	GPS/INS/Compass	Unlimited
GIS	DGPS/Acoustic/Compass	Unlimited

Table 4-2 shows the demonstrated accuracies for the systems' positioning solely by the navigation equipment for the known and unknown items in columns 2 and 3. In columns 4 and 5, the same points were acquired with the navigation integrated with the EM-61 sensor. The integrated positions were picked from the sensor peak reading from the profile of the survey line passing over the rebar points.

The CEHNC baseline DGPS equipment surveyed the known points as unknown and did not acquire the unknown points. The average error should be similar. GIS used the CEHNC DGPS equipment. Data was lost for columns 2-4 because of equipment interface failures. Results should be similar to CEHNC.

The Where Company UlTra system was set up just outside the test grids so it would not provide a mapping gap the grid interior. The grids were then surveyed by two setups. Its range was inadequate to capture the position of the far grid pins and needed the near ones for relative positioning reference. Because of the restrictive range, this system was unable to acquire the positions of any known or unknown points.

The average error was approximately the same for the known open points for the navigation only and the integrated system. The demonstrated average errors fall into three categories, with GPS the least accurate and fitting only for characterization roles. All other systems are capable of area mapping with the Where Company UlTra system being limited in work area by its short range. Only the two laser-based line-of-sight systems by Shaw and ArcSecond can support the accuracy required for interrogation.

Table 4-2
Unobstructed Average Error—Known and Unknown Points (in meters)

Demonstrators	Knowns (Open) (Navigation Equipment only)	Unknowns (Open) Navigation Equipment only)	Knowns (Open) (Integrated)	Unknowns (Open) (Integrated)
CEHNC (DGPS System)				
Average Error	0.301	Not acquired	0.352	0.663
Standard Deviation	0.231		0.101	0.427
Shaw/IT				
Average Error	0.038	0.070	0.038	0.160
Standard Deviation	0.019	0.114	0.020	0.051
Blackhawk				
Average Error	0.154	0.446	0.167	0.303
Standard Deviation	0.024	0.647	0.072	0.150
Where Company				
Average Error	Not acquired	Not acquired	Not acquired	Not acquired
Standard Deviation				
ENSCO				
Average Error	0.204	0.170	0.259	0.522
Standard Deviation	0.112	0.158	0.228	0.378
ArcSecond				
Average Error	0.066	0.126	0.069	0.142
Standard Deviation	0.018	0.086	0.023	0.095
Paper Pilot (Characterization)				
Average Error	1.484	3.293	3.621	4.450
Standard Deviation	0.963	1.536	1.089	1.480
GIS				
Average Error	Not acquired	Not acquired	Not acquired	0.580
Standard Deviation				0.303

Table 4-3 shows the demonstrated accuracies for the systems integrated with the EM-61 used to map the open Grids 1 and 4. All locations are for the subsurface anomalies as picked from the gridded geophysical data. The positions of the items in Grid 1 Lane 1 were given to assist in adjusting for site conditions to predict the unknown locations in Lane 2. Grid 4 was made more challenging by the inclusion of typical metal fragments.

Table 4-3
Unobstructed Average Error—Geophysical Subsurface Anomalies
(in meters)

Demonstrators	Subsurface Grid 1 Lane 1 Knowns (Integrated)	Subsurface Grid 1 Lane 2 Unknowns (Integrated)	Subsurface Grid 4 (Frag) Unknowns (Integrated)
CEHNC (DGPS System)			
Average Error	0.416	0.322	0.473
Standard Deviation	0.194	0.146	0.235
Shaw/IT			
Average Error	0.343	0.404	0.463
Standard Deviation	0.192	0.240	0.232
Blackhawk			
Average Error	0.184	0.434	0.952
Standard Deviation	0.185	0.200	0.707
Where Company			
Average Error	Not acquired	0.537	0.365
Standard Deviation		0.204	0.275
ENSCO			
Average Error	0.288	0.413	0.493
Standard Deviation	0.157	0.250	0.250
ArcSecond			
Average Error	0.233	0.374	0.303
Standard Deviation	0.185	0.271	0.229
Paper Pilot			
Average Error	Not acquired	Not acquired	Not acquired
Standard Deviation			
GIS			
Average Error	Not acquired	0.725	0.827
Standard Deviation		0.173	0.323

Neither the Where Company nor GIS reported out the locations of the Grid 1 Lane 1 known locations from the geophysical data analysis for comparison. Subsurface anomalies could not be evaluated for the Paper Pilot system since the large search radius required by the system's inaccuracy overlapped multiple anomaly locations. The average error ranges were 0.32-0.47 m for CEHNC, 0.34-0.46 m for Shaw, 0.18-0.95 for Blackhawk, 0.37-0.54m for Where Company, 0.29-0.49 m for ENSCO, 0.23-0.37 for Arsecond, and 0.72-0.83 m for GIS. Following gridding of data and picking the maximum geophysics response, the vastly different navigation system accuracies are no longer evident. Generally, an approximately 0.5 m search radius is required.

4.6 PERFORMANCE CRITERIA—OBSTRUCTED AVERAGE ERROR

Table 4-4 shows the demonstrated accuracies for the systems in the wooded obstructed areas with positioning solely by the navigation equipment and as integrated with the EM-61 sensor. The integrated positions were picked from the sensor peak reading from the profile of the line passing the rebar points. Testing with obstructions was limited to a 100 m range by the site layout. All systems met this range except for the Where Company UlTra system, which achieved a 30-36 m range. This short range did not permit that system to provide individual point positions.

Table 4-4
Obstructed Average Error—Known and Unknown Points (in meters)

Demonstrators	Unknowns (Woods) (Navigation only)	Unknowns (Woods) (Integrated)
CEHNC (DGPS System)		
Average error	Not acquired	1.077
Standard deviation		0.501
Shaw/IT		
Average error	0.095	0.423
Standard deviation	0.082	0.108
Blackhawk		
Average error	1.072	1.387
Standard deviation	0.771	1.565
Where Company		
Average error	Not acquired	Not acquired
Standard deviation		
ENSCO		
Average error	Not acquired	0.978
Standard deviation		0.247
ArcSecond		
Average error	0.385	0.368
Standard deviation	0.190	0.161
Paper pilot		
Average error	5.400	4.252
Standard deviation	5.581	1.932
GIS		
Average error		1.194
Standard deviation		0.688

CEHNC and GIS used the government's NovAtel 20-cm DGPS system. Average error was approximately triple that achieved in the open areas at 1.08 m for CEHNC and 1.19 m for GIS. Worth noting is that, although a 20-cm GPS is less accurate in the open than a 2-cm DGPS, it does perform better in obstructed areas since it continues working at degraded accuracy with partial loss of signal. Both demonstrators acquired positions only with the integrated systems. ENSCO also did not acquire separate navigation system-only locations for these points.

Shaw's system basically maintained the open area average error for navigation in the woods with the navigation-only system because of the well-planned setup with a clear line-of-sight. The integrated average error was approximately four times larger than the raw only. For integrated system locations, it ranked second best in the woods at 0.42 m. Blackhawk's 2 cm-capable DGPS dropped out and accuracy was maintained in the woods by the INS augmentation.

Average error was worse than the 20-cm DGPS supported systems at 1.39 m. The ENSCO system's average error degraded to approximately twice that of the open areas to 0.98 m. ArcSecond's average error degraded to approximately three times that of the open area to 0.37 m as the most accurate system. They were unique in that the navigation only and integrated average error was approximately the same. It was hypothesized that their average error was degraded by summing errors from multiple setups to transfer position control over a 300 m distance without tie points. Paper Pilot performed as expected and a rough GPS characterization system at 4.2-5.4 m average error.

Table 4-5 shows the demonstrated average error for the systems integrated with the EM-61 used to map the wooded East/West and North/South legs. All locations are for the subsurface anomalies as picked from the gridded geophysical data. CEHNC used the USRADS system with the stationary receiver's position being surveyed to provide the highest accuracy, as in a field deployment. This augmentation made average error twice that of the DGPS in the woods and approximately the same as the DGPS in the open, with average error at 0.35-0.48 m. Shaw's average error was approximately the same as in the open, areas at 0.31-0.42 m. Blackhawk's 2 cm-capable DGPS dropped out and average error was maintained in the woods by the INS augmentation. Average error was approximately the same as the fixed points at 1.14-1.36 m. The Where Company system surveyed the base station positions to provide the highest accuracy, as in a field deployment. Average error was 0.7-1.04 m. The ENSCO system's average error was approximately the same as the fixed points at 0.82-1.29 m. ArcSecond's average error degraded slightly to 0.46-0.57 m. Paper Pilot performed as expected and a rough GPS characterization system at 3.9 m average error for a limited test for a portion of the East/West leg. GIS was unable to complete the woods testing due to thunderstorms. Since this version relied upon the DGPS for primary positioning, it is believed that results would have been similar to the wooded point average error, as shown in Table 4-4, at no better than 1.2 m. Testing of systems that reacquired dig list points slightly increased accuracy. Neither Blackhawk, Where Company nor ArcSecond was able to report reacquired position points for evaluation. Results from the reacquired points show that the best systems, when tightly controlled, would require a 0.5 m search radius in the woods with others requiring 1-1.5 m.

The tree canopy was variable for the demonstrators with leaf coverage changes over the demonstration period. All GPS demonstrators had sufficient multipath problems to limit their accuracy. For the two laser line-of-sight systems and the radio navigation, the tree trunks and branches were the main obstructions. In the interior of the forest, there was little low vegetation to shadow visibility. What remained was cleared to create a pathway for the EM-61 integrated geophysical sensor, as would be typically performed as part of site preparation. Only the two laser-based systems by IT and ArcSecond met our objectives for area mapping accuracy.

Table 4-5
Obstructed Average Error—Geophysical Subsurface Anomalies (in meters)

Demonstrators	Unknowns (Woods) East/West Leg (Integrated)	Unknowns (Woods) North/South Leg (Integrated)	Reacquired Points
CEHNC (USRADS system)			

Demonstrators	Unknowns (Woods) East/West Leg (Integrated)	Unknowns (Woods) North/South Leg (Integrated)	Reacquired Points
Average error	0.477	0.353	0.342
Standard deviation	0.215	0.173	0.175
Shaw/IT			
Average error	0.420	0.309	0.215
Standard deviation	0.207	0.187	0.170
Blackhawk			
Average error	1.136	1.355	Not acquired
Standard deviation	0.465	0.724	
Where Company			
Average error	0.697	1.041	Not acquired
Standard deviation	0.297	0.410	
ENSCO			
Average error	0.820	1.299	0.676
Standard deviation	0.644	0.570	0.506
ArcSecond			
Average error	0.458	0.573	Not acquired
Standard deviation	0.188	0.494	
Paper pilot			
Average error	3.920	Not acquired	Not acquired
Standard deviation	1.705		
GIS			
Average error	Not acquired	Not acquired	Not acquired
Standard deviation			

- All demonstrators could provide basic setups in 10-20 minutes. The INS systems required additional time for calibration as well as the ArcSecond system to maintain high accuracies over larger areas. No times were considered excessive for any demonstrators.
- None of the demonstrators demonstrated multiple crew capability, but all had a procedure to make it possible by using different codes or radio channels.
- The ability to capture data in 3D was demonstrated by all except ENSCO, but data was not specifically evaluated. Observations noted were that 3D positions from all equipment that was not GPS-based were similar to the x-y position accuracy, with the laser systems also providing survey-level accuracy for elevations.
- All systems demonstrated at their most accurate capabilities with a form of selectable accuracy imposed by less care in setup and calibration, a greater travel speed, or more time between position updates. Reduced accuracy is only applicable to enhance productivity with reduced performance requirements.
- Shaw, ENSCO, ArcSecond and GIS demonstrated the ability to display position data in near-real-time.
- All systems were relatively easy to set up and operate by a two-person crew.
- All demonstrators could reacquire points.

4.7 TECHNOLOGY COMPARISON

The Paper Pilot system is applicable as a lightweight, inexpensive but also inaccurate, navigation basis for site characterization where a very large search radius is acceptable. The INS augmentation was unable to maintain position in obstructed areas, so this operated as strictly a card-based GPS system. This system should be used only in open areas with a good view of the GPS satellite constellation.

The CEHNC 20-cm commercial DGPS system gave reasonable accuracy in the open and was surprisingly accurate in the wooded area because the 20-cm system continued operation whereas the 2-cm DGPS systems drop out when they start to lose satellite lock. The USRADS was also used in the woods by CEHNC. With the stationary receivers surveyed, it provided very good positioning in the woods. USRADS performed much better than the Where Company ultrasonic system. Since they are based upon the same concept, it is assumed that the array of stationary receivers used by USRADS provides more accurate coverage than the single base station used by the UlTra.

The Blackhawk accuracy was comparable in the open to the results of the other vendor's integrated systems, but the INS was unable to maintain accuracy for the length of time needed without DGPS position refresh in the wooded areas. The INS application should be more applicable for relative positioning for short ranges and time periods.

The ENSCO system shows promise as a low-cost, easy-to-use moderately accurate system.

The most successful technology with the most value for the cost is the RTS, as demonstrated by Shaw. It can easily meet all accuracy needs in the open to acquire position accuracy to permit geophysical data analysis for discrimination. The system is survey-based so, to get good results, the application must be carefully planned with a higher level of user involvement and knowledge than that required for the ArcSecond system with similar accuracy.

The ArcSecond system matches the RTS performance for an approximately 100 m range. It is now easier to setup and, with four transmitters, is not significantly affected by the obstructions tested here. The current version, with long-range strobe enhancement, will permit accurate navigation while roaming in up to a 5-acre area. This system is perfectly suited for providing highly accurate three-dimensional data for moderate size areas and for dense geophysical mapping to interrogate chosen anomalies.

The GIS system accuracy was limited by the base positioning system and was similar to the CEHNC performance. Its strength for the next phase will be for relative positioning of reacquired anomalies for the creation of accurate interrogation data sets.

4.8 CONCLUSIONS

Navigation in the open and in obstructed wooded areas as demonstrated is still less accurate than was expected. In addition to the navigation systems, there are many factors that affect accuracy for final positioning. They include navigation system and setup errors, geophysical sensor

integration, the sensor's physical size, and the geophysical data gridding procedures and anomaly selection methodology using the procedures demonstrated here, a minimum search radius of 0.5 m is required for selected anomalies in the open areas and also for the laser-based systems in the woods. All other systems need a minimum of a 1-1.5 m search radius for the woods.
-*

- Additional efforts are needed to develop existing systems to meet desired accuracies to support geophysical mapping, reacquisitions and anomaly interrogation.
- Where applicable, the line-of-sight laser-based systems have the best performance for the cost.
- DGPS 20-cm systems can perform acceptably in the woods. Disabling the 2-cm DGPS capability to 20-cm for wooded surveys may be a viable moderate accuracy solution.

Complete summary results from the demonstration follow in Table 4-6.

5.0 COST ASSESSMENT

5.1 COST REPORTING

It is anticipated that technologies resulting from this demonstration will be available either to purchase or lease. Therefore, associated costs include:

- Capital purchase or lease cost
- Labor for mobilization and setup
- Labor for operations
- Labor for demobilization
- Maintenance (mainly battery replacement) and software upgrade

Costs are included in the individual demonstrator's reports. The final project report for ESTCP Project 200129 will provide system configurations and costs.

5.2 COST ANALYSIS

Cost Comparison

The demonstrated technologies are benchmarked to the baseline RTK DGPS for open areas and USRADS for wooded areas.

Cost Basis

Costs of the systems are based on purchase or lease price.

Cost Drivers

Additional drivers are time of setup and productivity. Both will be noted and converted to costs with typical loaded labor rates.

Life-Cycle Costs

Life-cycle costs include acquisition, operations, and maintenance. A 5-year system life will be assumed. No other costs are incurred.

6.0 IMPLEMENTATION ISSUES

6.1 ENVIRONMENTAL CHECKLIST

There are no permits or regulations that impact this technology.

6.2 OTHER REGULATORY ISSUES

This technology is not primarily driven by regulatory issues, but instead by desire for faster, more accurate, and more successful UXO operations. Information about this technology will be disseminated via technology conferences (such as the UXO Forum and the SERDP/ESTCP Symposium), by direct contact with appropriate government representatives working in UXO issues, and by direct contact with contractors who support government activities.

6.3 END-USER ISSUES

CEHNC is the lead on this project because of their pressing need for better technology for DGM and UXO operations. CEHNC is prepared to advocate applicable technologies into the user community if they are shown to meet the defined objectives.

7.0 REFERENCES

1. Innovative Navigation Systems to Support Digital Geophysical Mapping, UXO/Countermine Forum, September 3-6, 2002, Scott Millhouse, CEHNC. Paper was augmented with additional images and charts February 2003 and published as ESTCP Cost and Performance Report, (UX-0129) Innovative Navigation Systems to Support Digital Geophysical Mapping, February 2004.

2. Innovative Navigation Systems to Support Digital Geophysical Mapping, Phase II Demonstrations Final Workplan, 15 October 2002, Scott Millhouse, CEHNC.

3. Innovative Navigation Systems to Support Digital Geophysical Mapping, Phase III Demonstrations Final Workplan, 4 November 2003, Scott Millhouse, CEHNC.

4. Innovative Navigation Systems, Draft Phase 2 Final Report, April 2003, John E. Foley, Ph.D., Shaw Environmental and Infrastructure Corp.

5. Demonstration and Development of Innovative Navigation Equipment and Methodologies to Support Accurate Sensor Tracking in Digital Geophysical Mapping (DGM) Surveys, Phase 2 Engineering Evaluation Report Final Draft, Jan 14, 2003, Mark Blohm, Blackhawk Geosciences.

6. Long Range UlTra System, Final Report, Revised 29 April 2004, Scott Millhouse, CEHNC.

7. UXO Precise Position Tracking Demonstration, Draft, Final Report, 1 Apr. 2003, ENSCO Inc., David W.A. Taylor, PhD, PG.

8. McKinley Range Navigation Demonstration, 14 Nov. 2002, Edmund Pendelton, ArcSecond Inc.

9. Innovative Navigation Systems to Support Digital Geophysical Mapping, Navigation System Report, 15 Nov. 2002, Mark R. Andersen, Paper Pilot Research Inc.

10. GeoVizor McKinley Range Prove-out, July 13, 2003, Matthew Gifford, Gifford Integrated Sciences.

8.0 POINTS OF CONTACT

Demonstrator	Point of Contact	Address	Phone/Fax/Email	Role in Project
CEHNC	Scott Millhouse, PE	U.S. Army Corps of Engineers Engineering and Support Center-Huntsville 4820 University Square Huntsville, Alabama 35816-1822	Ph: 256-895-1607 Fax: 256-895-1602 scott.d.millhouse@ hnd01.usace.army.mil	Principal investigator and independent baseline
Shaw/IT Corp	John E. Foley, Ph.D.	IT Corporation 15 Douglas Road Lowell MA, 10852	Ph: 978-458-9807 Fax: 978-458-0278 jfoley@TheITGroup.com	Demonstrator
Blackhawk GeoSciences, Inc.	Mark Blohm	Blackhawk GeoSciences, Inc. 301 Commercial Road, Suite B Golden, CO. 80401	Ph: 303-278-8700 Fax: 303-278-0789 mark@blackhawkgeo.com	Demonstrator
Where Company	Robert R. Highfill, MA, MS	Where Company 114 Norway Lane Oak Ridge, TN 37830	Ph: 865-483-7252 Fax: 815-550-4565 roberthighfill@comcast.net	Demonstrator
ENSCO, Inc.	David W.A. Taylor, PhD, PG	ENSCO, Inc. 5400 Port Royal Road Springfield, VA 22151	Ph: 336-632-1200 Fax: 703-321-7863 taylor@ensco.com	Demonstrator
ArcSecond, Inc.	Edmund Pendleton	ArcSecond, Inc. 44880 Falcon Place, Suite 100 Dulles, VA 20166	Ph: 703-435-5400 Fax: 703-435-5994 edmundp@arcsecond.com	Demonstrator
Paper Pilot Research Inc.	Mark R. Andersen	Paper Pilot Research, Inc. P.O. Box 650776 Sterling, VA 20165-0776	Ph: 571- 434-9633 Fax: mra@P2Ri.com	Demonstrator
GIS	Matthew Gifford	Gifford Integrated Sciences 31859 Rainbow Hill Road Golden, CO 80403	Ph: 303-277-9821 Fax: 303-271-1867 matthew.gifford@att.net	Demonstrator

Signature of Project Lead

D. Scott Millhouse — 25 June 2004

Scott Millhouse, PE — Date

Appendix A: Analytical Methods Supporting the Experimental Design

Not required.

Appendix B: Analytical Methods Supporting the Sampling Plan

Not required.

Appendix C: Quality Assurance Project Plan (QAPP)

C.1 Purpose and Scope of the Plan

The purpose of this plan is to outline the quality assurance procedures for this project.

C.2 Quality Assurance (QA) Responsibilities

The QA officer for this demonstration is Scott Millhouse, CEHNC. He will oversee the demonstration, assure compliance with the Work Plan, and attest to the results.

C.3 Data Quality Parameters

The most important aspect of quality assurance for this demonstration is that all measurements are accurately recorded and well documented. Detailed signed and dated field notes will accompany all digital data files. The QA officer will independently evaluate performance for the unknown areas of the grids and compare navigation accuracy and geophysical anomaly representations with past test results and the actual values and locations. A comparison matrix will be created showing field results as benchmarked to the known locations.

C.4 Calibration Procedures, Quality Control Checks, and Corrective Action

To be determined, as required by individual demonstrators

E.5 Demonstration Procedures

Demonstration procedures are described in the test plan. The only maintenance anticipated during the demonstration is exchange or recharging of batteries.

In addition to the demonstration procedures, the QA officer and demonstrator will take digital photographs during conduct of the demonstration.

E.6 Calculation of Data Quality Indicators

Data quality for this demonstration primarily consists of accurate recording of data. The QA officer will observe the recording of all data.

E.7 Performance and System Audits

Data will be reviewed at the completion of a work task by the QA Officer with the demonstration team.

E.8 Quality Assurance Reports

The QA officer will attest to the correctness of the information acquired during the demonstration by signature of the Demonstration Report.

E.9 Data Format

All handwritten data and field notes will be written legibly, in ink, and signed and dated by the note taker. Any entries that are corrected will be done with a single strike-through and will be initialed by the note taker.

Most data collected during this demonstration will be digital and stored on computer disks in industry standard PC formats.

Appendix D: Health and Safety Plan

This demonstration will be conducted in compliance with the existing Health and Safety Plan at the McKinley Range, Redstone Arsenal, Alabama.

Appendix E: Data Storage and Archiving Procedures

Field notes will be recorded in a bound surveyor's notebook. Electronic data will initially be stored in the field on computer disks. Prior to leaving the field each day, all data will be copied onto CD-R disks for permanent storage. A copy will be provided to the QA officer.